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Annual Progress Report for NASA Astrophysics Theory Program Grant NAG 5-3099:

A Systematic Study of Explosions in Core Collapse Supernovae

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Contents

1 Summary

During the first eight months of research funded under this grant we have made substantial progress towards our systematic study of explosions in core collapse supernovae. The work has largely progressed as we originally anticipated in our project proposal. The start date of this grant was October 15, 1995. We had originally requested a start date of January 1, 1996 because of prior commitments of the PI. For this reason major work on this project began in January 1996 and consequently the work described in this progress report has principally taken place in the first seven months of this year. Nevertheless we have largely maintained the schedule we anticipated in the original proposal. We have substantial progress in a number of areas: numerical radiation-hydrodynamics algorithms for convective supernova models and late-time fall-back models, the study of how to accurately implement neutrino-matter interactions, the study of neutrino-transport approximations, and the study of equation of state issues. We discuss each of these in the next few sections.

2 Numerical Models of Supernovae

We have made major modifications of the ZEUS-2D Eulerian hydrodynamics code, developed by Stone, Norman, and Mihalas [1, 2], in order to be able to conduct 2-D simulations of convection in the post-bounce epoch supernovae. Because of the extent of the modifications, carried out by D. Swesty, we now refer to version of ZEUS-2D as SNZEUS ("SuperNova-ZEUS"). Using SNZEUS we have been conducting two dimensional simulations of the post-bounce epoch of supernovae. To date most of these simulations have been conducted using high radial resolution and low angular resolution. These simulations have been in support of the studies of how the equation of state (EOS) and neutrino-matter interaction rates affect the models. The reason for low angular resolution is to effect a savings in CPU time while generating maximum number of different models in order that we may learn how the microphysics numerically enters into the models. Once this work is complete all future models will be carried out with high angular resolution. We have carried out a few high angular resolution models thus far to fully test the hydrodynamics algorithms. We have also discovered a new approach for treating the core of the supernova. Unlike [3] or [4] we numerically model the entire core with the 2-D Eulerian code. However, interior to the proto-neutron star we constrain the hydrodynamic motion to be purely radial, thus circumventing the otherwise restrictive CFL condition.

During this period D. Mihalas and D. Swesty have also continued our work on the THOR 1-D adaptive mesh code which we will employ in the later stages of this project to study the fall-back onto the compact object remaining after the explosions. This work will result in at least two papers on the code itself in the near future. The first of these papers is complete and it awaits the completion of the second paper so that they may be submitted together.

In order to further our systematic study of the role of the neutrino transport algorithm D. Mihalas has been working on implementations of Accelerated Lambda Iteration (ALI) methods for 2-D transport in spherical coordinates. The use of ALI will allow us to calculate variable Eddington factors that contain the full angular dependence of the radiation flow. This, in turn, will provide us with a means of implementing radiation transport, with closure at the level of the second moment, in a truly accurate manner. Once this work is complete we will conduct simulations comparing these models to flux-limited diffusion models.

As we mentioned in the original proposal we will need to conduct 3-D radiation-hydrodynamic simulations for the later stages of this project. For this reason M. Norman, in conjunction with NCSA research programmer Robert Fiedler, has been working on a fully massively parallel version of the ZEUS-3D code, which will be called ZEUS-MP, that we will employ to conduct fully 3-D radiation-hydrodynamic simulations of supernova. Further work is now being conducted on implementing radiation transport algorithms into this code in two approximations: the unconditionally–stable product formula algorithm of [5] and the more traditional flux-limited diffusion approximation.

3 The Role of the Neutrino Transport Algorithm

As we pointed out in the proposal for this project the accuracy of the neutrino transport algorithm could prove crucial to success or failure of explosive models of core collapse supernovae. We have systematically begun to study how various approximations made in the neutrino transport algorithm can affect the models. We have found several interesting results. First, by comparison of the grey and multi-group approximations in 1-D models, we have found the grey approximation employed in all current 2-D supernovae models can differ substantially with respect to neutrino energy densities, luminosities, and spectra. Second we have discovered that the grey models when employed in 2-D calculations are extremely sensitive to the the choice of neutrino-matter thermal decoupling criterion. By changing the decoupling criterion within the limits of our high radial resolution models we have been able to vary the electron neutrino luminosities by nearly an order of magnitude. The neutrino spectra and thus the rate of neutrino heating outside the neutrinosphere are consequently strongly affected by this variation. We are continuing to investigate this in order to see what affect this has in forming convectively driven explosions. Furthermore, since nucleosynthesis is very sensitive to ratios of the electron neutrino and electron anti-neutrino fluxes the we believe that this may have a substantial effect on nucleosynthetic yields and we are beginning to investigate this issue. We have also implemented the neutrino transport in our code in a manner so as to be able to compare the radial approximation employed by [3] with fully 2-D transport models. We have begun to run models that will allow us to determine how accurate this approximation really is. These results are being prepared as a paper that will be submitted to the Astrophysical Journal.

4 Neutrino–Matter Interaction Rates & Equation of State

As part of our effort to provide a systematic study of the core collapse supernova problem D. Swesty has been investigating the details of how various neutrino–matter interaction rates can be implemented in the grey approximation. This has included detailed comparisons between the grey approximation and full multi-group calculations in 1-D simulations. This work has revealed a number of surprising results that may strongly influence how the flux for neutrinos couples to the matter.

One of the most interesting results we have obtained so far involves how the electron-capture rates are implemented in the grey approximation. Since the computational cost of using a multi-group treatment of neutrino transport in 2-D or 3-D simulations is extremely high virtually all 2-D models carried out to date have used this grey approximation. However it has long been suspected that the grey approximation can give substantially different results from a more accurate full multi-group treatment. We have found that the method used by [3, 6, 4] to implement the electron capture rates do not allow the correct chemical equilibrium point in the collapsed core to obtain. In fact the electron fraction that obtains in the core can differ from the correct value of $Y_e \approx 0.37 - 0.38$, as determined by full multi-group calculations, by as much as a factor of 1/2. This has a dramatic affect of the neutrino energy densities and the structure of the proto-neutron star. We are presently working on an implementation of electron rates that yields more accurate results. We have also found inaccuracies in the way other rates for process such as neutrino–electron scattering are implemented in the grey approximation. We are preparing a paper for submission to Ap. J. Letters discussing these issues.

We have also progressed in our study of the role of the EOS in the explosion mechanism as was discussed in our original proposal. We have run a number of models using various EOS implementations in order to try an understand what role the EOS plays in the models. One result we have obtained is that tabular equations of state, which have been employed in other multi-dimensional models [3], can result in substantial temperature errors in the core unless one can guarantee thermodynamic consistency. This in turn leads to substantial differences in the neutrino spectrum in the core and the neutrino matter interaction rates. We are continuing work in this area as well as in the other areas where the EOS may directly affect convective dynamics. We have also used thermodynamically consistent techniques to construct accurate EOS tables for various nuclear symmetry energy parameters. Using these tables we will soon conduct parameter studies of convective explosion models to see how the convection dynamics is influenced by the electron capture rate which is dependent on the symmetry energy parameter. Our work on the role of the EOS in convective dynamics is being prepared as a paper to be submitted to the Astrophysical Journal.

5 Publications

During the first eight months of this project we have completed work that will result in a number of papers. Because the work described in this progress report covers only the first phase of this project only a portion of this work is complete enough to have been submitted and accepted for publication. The remaining work is being prepared for submission at this point in time. The support of this grant has resulted in the following papers that have been accepted or are in preparation:

1. "Thermodynamically Consistent Interpolation for Equation of State Tables" *To appear in The Journal of Computational Physics*
2. "Adaptive Mesh General Relativistic Multi-Group Radiation Hydrodynamics in Spherical Symmetry: I. Formalism and Equations" *To be submitted to the Astrophysical Journal*
3. "Adaptive Mesh General Relativistic Multi-Group Radiation Hydrodynamics in Spherical Symmetry: II. Finite Differencing, Numerical Implementation, and Hydrodynamic Algorithm Tests" *In preparation for the Astrophysical Journal*
4. "Radiation-Hydrodynamic 2–D simulations of Convection in Supernovae II: Neutrino Transport Algorithms" *In preparation for the Astrophysical Journal*
5. "The Implementation of Neutrino–Matter Interaction Rates in 2–D Supernova Models" *In preparation for the Astrophysical Journal Letters*
6. "Radiation-Hydrodynamic 2–D simulations of Convection in Supernovae I: Equation of State and Neutrino–Matter Interactions" *In preparation for the Astrophysical Journal*

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Final Technical Report
for NASA Grant NAG8-285

Dear Mr. Sweigart:

During the period March 1993 through September 1995 our research was supported in part by NASA grant **NAG8-285** to study massive X-ray binaries with Ginga data. Those involved in this research included, in addition to myself, a postdoc Jonathan Woo, my graduate student Christopher Becker, and three undergraduate research assistants who were participating in MIT's UROP Program.

Nitin Kastori (a sophomore at the time), Dr. Alan Levine, and I analyzed the ~0.02 Hz quasiperiodic oscillations in the intensity of the X-ray pulsar SMC X-1. The analysis was successfully completed, including the use of a number of different approaches. However, no definitive conclusions could be reached concerning the mechanism or the underlying physics that produces the QPOs, and we decided against publishing the results.

During his junior year, Mark Bockrath investigated a new semianalytic approach (coupled with a novel, fast numerical integration scheme) to calculate X-ray spectra, including fluorescent lines from low-Z elements, during the eclipse of massive X-ray binaries. The utility of the technique was verified, and the results were used to predict what the ASCA imaging X-ray spectrometer would observe from these systems. The technique and results have not been written up for publication.

Dr. Woo has extensively utilized the Ginga database to determine the most up to date values of $a_x \sin i$ and eclipse profiles for five binary X-ray sources. The eclipse profiles can be used to interpret the radial extent of the companion star at X-ray 'optical' depth unity. To this end, Jon Woo has been collaborating with Dr. John Blondin (North Carolina St. University) to carry out self-consistent hydrodynamics calculations of the stellar wind outflows from the massive companions under the influence of X-ray heating from the neutron star. Once a circumstellar density profile has been generated from the hydrodynamics calculations, Dr. Woo checks the consistency of the results against the Ginga observations by carrying out Monte Carlo scattering calculations that describe the propagation of the X-rays and their fluorescent products through the circumstellar material to the observer. This portion of the research is now very near to completion. The results of these detailed studies are then incorporated into an analysis code, utilizing Monte Carlo techniques, to refine the binary system parameters for these sources. The parameters include the neutron star mass; the mass, radius, moment of inertia, and evolutionary state of the donor star; and the stability of the system against tidal decay. This grant also provided a portion of the funds for Dr. Woo to travel to Japan to extract the appropriate Ginga data at ISAS, and to attend a workshop on X-ray spectra in Tokyo.

In summary, a number of interesting research projects utilizing, or motivated by, the Ginga data were carried out during the tenure of this research grant. The research involved three undergraduate students, one graduate student, a postdoc, and myself. Due to a variety of unique circumstances (e.g., the advent of ASCA with better spectral resolution than Ginga, and RXTE with larger detector area and superior timing capabilities) we did not feel that publication of two of the results was warranted. However, we do plan a major publication on our studies of the system parameters of the five massive X-ray binaries, as well as a detailed description of the analysis and interpretation techniques which involve the hydrodynamics and scattering calculations.

Sincerely,

Saul Rappaport

Saul Rappaport
Professor of Physics